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THEORETICAL INVESTIGATION OF CURRENT INSTABILITIES AND TERAHERTZ OSCILLATIONS IN A TWO-DIMENSIONAL ELECTRON FLUID

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The purpose of this work is to develop firther the theory of novel mechanisms for generation and detection of electromagnetic radiation in the terahertz range using the plasma oscillations of the two dimensional electron fluid in a Field Effect Transistor (FET). We have shown previously that the motion of electrons in a FET under certain conditions is described by hydrodynamic equations which coincide with those for shallow water, and that the current-carrying state is unstable against plasma wave generation in the terahertz frequency range. In this work we have 1)Performed extensive numerical simulations of the strongly non-linear regime of plasma oscillations build up as a result of this instability. We have found highly regular non-linear oscillations related to traveling voltage jumps which are analogous to the so called hydraulic jumps in shallow water, or shock waves in a gas 2)Proposed and studied the possibilities of using a FET as a tunable resonant terahertz detector, mixer and multiplier. Preliminary experiments performed at relatively low (tens of GHz) frequencies have confirmed our theoretical predictions.

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SUMMARY

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Keawords: terahertz radiation, infrared radiation, plasma waves, shallow water, instability, two dimensional electron fluid, Field Effect Transistor.

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1. STATEMENT OF THE PROBLEM

The purpose of this work is to develop firther the theory of the two dimensional electron fluid in a Field Effect Transistor (FET), and to study its possible applications to terahertz electronics. It was shown by M.I.Dyakonov and M.S.Shur [1] that at normal concentrations and not very low temperatures the motion of the electron fluid in the FET channel is described by hydrodynamic equations which coincide with those for shallow water [2], and that the steady state with a dc current is unstable against plasma wave generation. In submicron gate FETs the plasma oscillation frequency is in the terahertz frequency range. This spectral range has a significant potential in complementing the microwave and infrared bands for remote sensing, atmospheric profiling, surveillance etc.

In this work we study:

1)The strongly non-linear regime of plasma oscillations, well above the threshold . It is of great theoretical interest, as well as of practical importance, to understand the nature of non-linear oscillations which are built up as a result of the instability discovered in Ref. 1. It is usual in hydrodynamics, that instabilities lead to highly irregular behaviour (turbulence), and this is what we expected to see. We show that, surprisingly, this is not the case, and that very regular non-linear oscillations emerge as the result of the plasma wave instability.

2)The possibility of using the non-linear properties of the two dimensional electron fluid in a FET for detection, frequency mixing, and frequency multiplication of terahertz radiation. The advantage of such a FET-based detector would be its resonant nature and, as a consequence, its tunability, since by simply changing the gate-to-channel voltage one may change the resonant frequency, corresponding to the fundamantal mode of plasma oscillations.

2. BACKGROUND

Plasma waves in a FET channel were predicted theoretically [3,4] and observed experimentally in Silicon Metal-Oxide-Semiconductor inversion layers by absorption of far infra-red radiation [5]. Some very weak emission at the plasma frequency was also observed [6] due to the Smith-Purcell effect in Silicon with modulated gate. It was recently shown [1,7] that in short FETs where electrons

experience practically no collisions with impurities and/or phonons during the transit time, but where high electron concentration results in many electron-electron collisions, the two dimensional (2D) electrons exhibit interesting hydrodynamic behaviour. Such is the case for high-mobility devices with 2D electron concentration 10^{12} cm^{-2} at nitrogen or even room temperature, when the Fermi energy, the Bohr energy and the thermal energy kT are roughly equal.

We have shown previously [1], that in such conditions the electrons are described by hydrodynamic equations which are exactly the same as those for shallow water [2], the water level corresponding to the gate-to-channel voltage. The shallow water waves correspond to the plasma waves in the FET channel. These waves have a linear dispersion law with a velocity s given by the formula

$$s = (eU/m)^{1/2} ,$$

where e is the electron charge, m is the electron effective mass, and U is the gate-to-channel voltage swing. The value of s is typicaly on the order of 10^8 cm/s. Thus, for submicron gate length, L , the plasma oscillation frequency which, for the fundamantal mode is on the order of s/L , lies in the terahertz frequency range. This frequency can be easily tuned by changing the gate voltage U.

It was also shown in Refs. 1,7, that for the boundary conditions of a short-circuited (at high frequency) gate-source, and open gate-drain, the steady state of a current-carrying FET is unstable against spontaneous generation of plasma waves. This instability is due to the plasma wave amplification during reflection at the drain side of the channel (the reflection coefficient

$$R = \frac{s + v_0}{s - v_0}$$

is greater than unity, because of the difference in velocities for waves travelling in opposite directions; the velocities are $s+v_0$ and $s-v_0$, where v_0 is the drift electron velocity).

Because of the shallow water analogy, various new hydrodynamic phenomena should take place in the electron fluid in a FET, such as the "choking" effect [8], shock waves and soliton propagation. This opens a new field of studies of the two dimensional electron fluid properties.

We have previously studied analytically the weakly non-linear regime of plasma oscillations, just slightly above the instability threshold [9], as well as different mechanisms of generation of terahertz radiation in a FET [10,11].

3. THEORETICAL APPROACH

The theoretical approach utilized in this work is based on the hydrodyanamic equations derived in Refs. 1,7. These include the Euler equation of motion for the electrons, the continuity equation, and the linear relation between the surface electron concentration in the channel and the gate-to-channel voltage swing. We assume that this relation is valid locally even in the case when the voltage swing varies in space (the "graduate channel approximation"), which is true if the spatial scale of the voltage variation is large compared to the gate-channel separation.

In the equation of motion we include dissipation terms due to both external friction (caused by collisions of electrons with impurities and/or phonons) and internal friction (caused by electron-electron collisions, resulting in the viscosity of the electron fluid). The viscosity of the electron fluid, just like in normal fluids, can not be calculated exactly for the case of strongly interacting electrons, which is if interest to us. It may be, however, easily estimated, assuming that the mean free path for electron-electron collisions is on the order of the interelectronic distance, as explained in Section 2. We find that the viscosity is relatively small, however in some cases it should be taken into account.

Effects of heating of the electron fluid are neglected in this work, which is justifiable at low enough fields and low current values.

In studying the strongly nonlinear oscillations well above the instability threshold, we use computer simulations and numerical methods, developed for solving similar problems in hydrodynamics [12]. In our theory of resonant detection of terahertz radiation by the electron fluid we assume that the incoming ac signal has a small amplitude, so that nonlinear effects are small. For this practically important case we develop an analytical theory, based on the solution of the basic equations.

In all of our studies we restrict ourselves to one dimensional problems, i.e. we assume that the electron concentration and drift velocity depend on one coordinate only, and that everything is uniform in the other direction.

4. NUMERICAL STUDY OF THE NONLINEAR REGIME OF PLASMA OSCILLATIONS

The nonlinear evolution of the current instability in the two-dimensional electron fluid [1] is studied with the use of computer stimulations [13]. One may expect that, as a result of the instability, a chaotic motion of the electron liquid should emerge. However, our simulations show that the instability development results in establishment of stationary periodic oscillations everywhere over the investigated region of parameters. In the case of small increments (close to the instability threshold) the oscillation amplitude is small and well described by our previous analytical theory [13]. For high enough increments, i.e. well above the threshold, steplike distributions of electron concentration and velocity analogous to shock waves, or hydraulic jumps, are formed in the FET channel.

We solve numericaly the basic hydrodynamic equations established in Ref. 1 with appropriate boundary conditions, using the method proposed by Broilovskaya (see Ref. 12) for solving hydrodynamics problems.

Simulations clearly show that the current instability leads to stationary periodic nonlinear oscillations, whose nature does not depend on the initial conditions. An example of results obtained is presented in Figs. 1 and 2, where z and τ are the dimensionless coordinate and time, $u(z,\tau)$ is the dimensionless gate-to-channel voltage, and u_d is the dimensionless drain voltage (the voltages are measured with respect to the applied source voltage). The growth of the initial fluctuation and the shape of the stationary drain voltage oscillation are given in Fig. 1. There are four phases, marked by A,B,C, and D, during each oscillation period. The voltage distribution along the FET channel during these four phases are presented in Fig. 2(a) - 2(d).

At the phase (A), there is a jump in the voltage distribution, which moves from the drain where it appears, to the source [Fig. 2(a)]. At the phase (B), the jump is reflected from the left boundary of the FET (source) and then disperses, moving to the drain [Fig. 2(b)]. This behaviour of the jumps correlates well with the theory of hydraulic jumps [2]. Indeed, it can be readily shown from this theory that the jump is stable when it moves upstream (from right to left) and should disperse when it moves downstream (from left to right). At phases (C) and (D) , there are relatively smooth voltage distributions that move from drain to source at phase (C) and in the opposite direction at phase (D). It is astonishing that this complex behaviour is regularly reproduced over each oscillation period.

We note that chaotic behaviour was never observed in our simulations. This is favorable for applications of the current instability in a ballistic FET for generation of terahertz electromagnetic radiation.

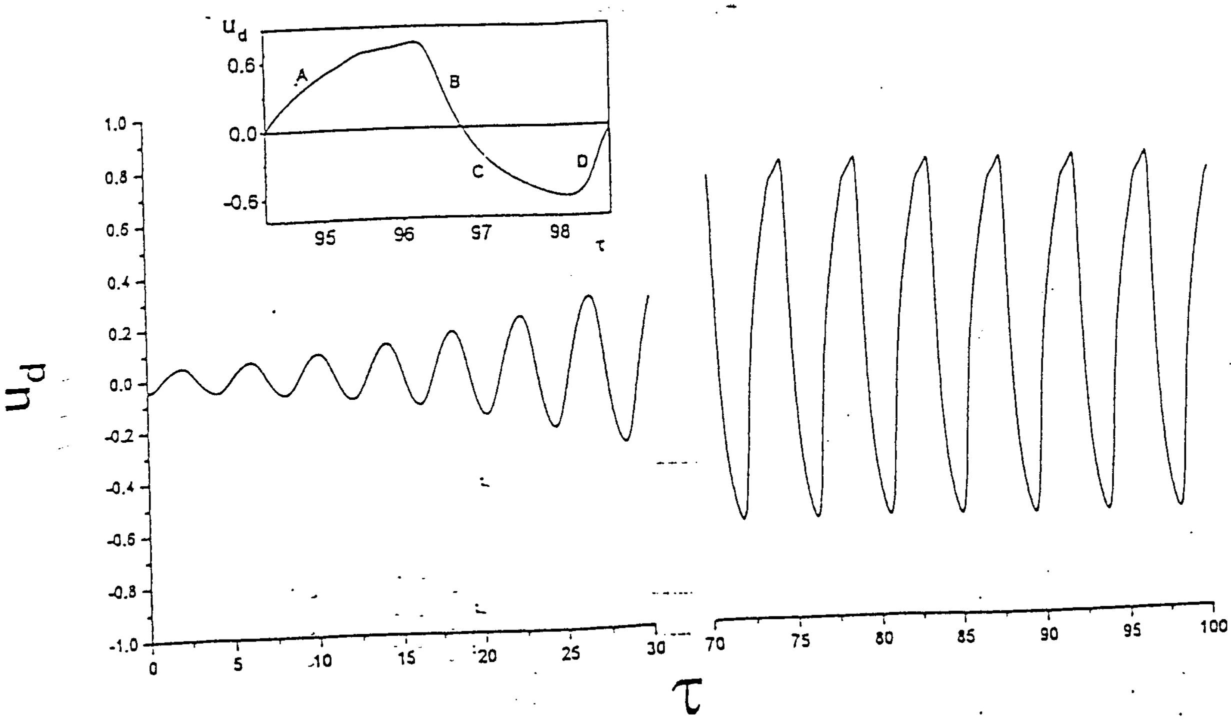

Fig. 1. The development of current instability and establishment of stationary nonlinear plasma oscillations. Insert shows the form of the stationary drain voltage oscillation over one period.

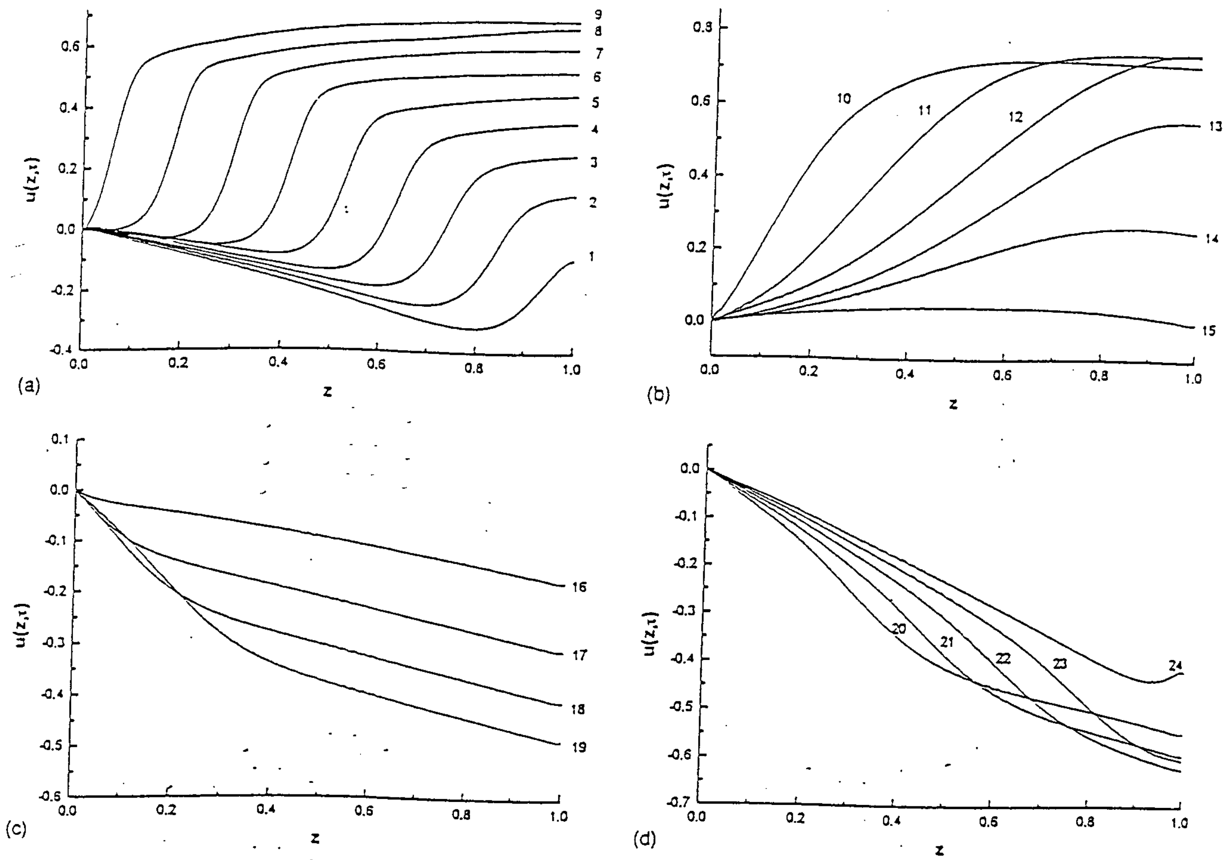

Fig. 2. The voltage distribution along the FET channel at different moments with equal time intervals within one period of stationary oscillations. (a) - (d) correspond to the four phases (A) - (D) marked in the insert in Fig. 1. Numbers at the curves indicate their sequence in time. One can see the propagation of a shock-wave-like voltage jump in (a).

5. FIELD EFFECT TRANSISTOR AS A TUNABLE RESONANT TERAHERTZ DETECTOR, MIXER, AND MULTIPLIER

In our proposed detector [14] the incoming electromagnetic radiation induces an ac voltage at the source side of the FET channel. The drain side of the channel is an open circuit. This can be easily achieved using an appropriate antenna structure. The ac voltage excites the plasma waves, with a velocity, s, determined by the dc gate-to-source voltage (see Section 2). Because of the nonlinear properties of the electron fluid and the asymmetry in the boundary conditions, a FET biased only by the gate-to-source voltage and subjected to an electromagnetic radiation develops a constant drain-to-source voltage, which has a resonant dependence on the radiation frequency with maxima at the plasma oscillation frequency and its odd harmonics.

Thus, the FET acts as a tunable resonant quadratic detector of electromagnetic radiation in the terahertz range. The sensitivity of this detector is determined by the quality factor, Q, of the resonator for plasma waves, which is formed by the FET channel together with the source and drain contacts. In turn, the quality factor is determined by the losses due to viscosity and collisions. Our estimates show that for submicron devices Q may easily reach the value of 10.

In our theoretical study [14, 15] we calculate analytically the dc responce of a FET to the incoming electromagnetic radiation. We find that the relevant parameter is $Q = s\tau/L$, wher s is the plasma wave velocity, τ is the characteristic damping time due to collisions, and L is the device length. When Q is large (short device) FET acts as a resonant detector with responsivity which is proportional to Q^2. We show that, at the resonance peak, the FET responsivity can exceed typical responsivities of standard Schottky barrier detectors (which are on the order of 1000 V/W) by 2-3 orders of magnitude. A longer device, for which the value of Q is small, acts as a broad band detector with responsivity comparable to that of Schottky barrier detectors. In this case, the plasma waves are axcited by the incoming radiation at the source, but they decay before ever reaching the drain side of the channel.

Nonlinear properties of the 2D electronic fluid lead not only to the rectification of the incoming radiation but also to the appearance of the signal at the second and higher harmonics of the incoming radiation with the resonance response at the fundamental plasma frequency. As expected, the second harmonic has a larger magnitude than higher harmonics. For the second harmonic, the voltage has a maximum closer to the source end of the device channel, which should be accounted for in the multiplier design. The amplitude of the second harmonic is roughly of the same order as the dc voltage developed in the resonant detector. We have also shown that the same physics leads to mixing of weak incoming signal with a strong local oscillator signal, which is often more desirable in practical systems because of much higher sensitivity.

In collaboration with Michael Shur's group in the University of Virginia we have performed preliminary experiments to check our theory [16]. The experiments were done on GaAs and GaN HEMTs in the range of comparatively low frequencies 6-20 GHz. In this frequency range the plasma waves are overdamped, and the detector operates in the broad band mode, rather than in the resonant mode. However, we found and measured the dc response, and studied its frequency and gate voltage dependencies, which were in an excellent agreement with our theoretical predictions.

6. CONCLUSIONS AND RECOMMENDATIONS

In this work we have studied theoretically several problems related to the nonlinear hydrodynamic behaviour of the two dimensional electron fluid in the channel of a Field Effect Transistor. The most important physical feature of this system is the existence of plasma waves with a linear dispersion law. The FET channel together with the source and drain contacts forms a resonator for plasma oscillations with a quality factor about 10 for submicron devices.

By computer simulations we have studied in detail the consequences of the direct current instability discovered in Ref. 1. We found that, as the instability develops, eventually periodic stationary oscillations are established, which are acompanied by travelling voltage jumps in the FET channel. These results should be important for the design of FET terahertz oscillators excited by dc current.

We have proposed and analyzed theoretically a new type of tunable resonant terahertz detectors, mixers, and multipliers utilizing the nonlinear properties of the electron fluid in the FET channel. Preliminary experiments on the detection of electromagnetic radiation by a FET, performed in the low frequency range, have confirmed our theoretical predictions. The problem now is to move to the terahertz frequency range, where the advantages of this new type of detector, depending on its resonant character and tunability, should be much more spectacular.

We should emphasize that devices operating at terahertz frequencies become inseparable from the circuit. Therefore, issues related to coupling plasma waves to electromagnetic radiation, to antenna structures for electromagnetic radiation, and to device integration with submillimeter circuits will have to be addressed for practical implementation of plasma wave electronic devices. Since the plasma wave velocity is much smaller than the light velocity and the device dimensions are much smaller than the electromagnetic wavelength corresponding to the plasma frequency, antenna structures, which are much larger than typical devices are needed for coupling plasma and electromagnetic waves. These issues and the antenna and circuit design will be similar to those currently investigated for deep submicron Schottky diodes operating in the terahertz range.

It seems that a new field, which we name "plasma wave electronics", may emerge as a result of our findings, and a new generation of terahertz devices, utilizing plasma oscillations in submicron FETs, such as oscillators, detectors, mixers, and frequency multipliers, could be implemented.

The results obtained in the course of this work were published in Refs. 13 - 16

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